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Climate of the Pinyon-Juniper Zone of the Great Basin

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FINAL REPORT

Climate of the pinyon-juniper zone of the Great Basin

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ABSTRACT

THE CLIMATE OF THE PINYON-JUNIPER ZONE OF THE GREAT BASIN

The pinyon-juniper (*Pinus monophylla-Juniperus osteosperma*) woodland occurs on parts of the slopes of the mountains of the Great Basin. Because very few climate stations are located in the woodland, its climate must be described by data interpolated and extrapolated from locations outside the woodland. In this study, methodology for a water balance climatology of the pinyon-juniper zone was developed.

The mean precipitation input to the water balance may be estimated by using: 1) a statistical relationship between latitude, longitude, elevation, and measured precipitation in the Great Basin, or 2) a statistical relationship between precipitation at valley stations, topographic features near the locations and precipitation at mountain stations.

The evapotranspiration output from the soil water may be estimated by using a radiation based evapotranspiration model combined with a Thornthwaite type soil water budget. Equations were developed which estimate solar radiation on any surface (specified by latitude, elevation, slope angle, and aspect) given percent possible sunshine from one or more airport locations. The evaporation equivalent of the solar energy is adjusted for local temperature, humidity, and wind. The temperature may be approximated from data at valley stations, the humidity (as vapor pressure), and wind may be interpolated and extrapolated from airport locations. The actual evapotranspiration may be calculated for any assumed plant coefficient and the water budget of the soil calculated.

Mean values of the water budget for selected surfaces were in qualitative agreement with field vegetation patterns. The synoptic analysis of daily precipitation data demonstrated that although mean precipitation could be estimated adequately, individual weekly or monthly data were so highly dependent on local storms that interpolation was not feasible. Local extreme precipitation or other extreme weather events may be a dominant component of the climate of the pinyon-juniper zone. -- Richard O. Gifford, Univ. Nevada-Reno, June 1980.

FINAL PROJECT REPORT

THE CLIMATE OF THE PINYON-JUNIPER ZONE IN THE GREAT BASIN

Richard O. Gifford

Introduction

Pinyon pine and juniper in mixed communities and in single species stands are associated with a variety of shrubs, grasses and forbs, in a wide range of sites in the Western United States. Several species of pine and several species of juniper, as well as scores of associated species are found in this broad woodland type. This project was concerned with part of one of the pinyon-juniper associations in the United States: *Pinus monophylla-Juniperus osteosperma*. The geographical area considered is the major part of the Great Basin where these two species are found in mixed communities or in pure stands near each other. The boundaries are arbitrary since both species are found outside the limits of the area chosen. The parts of this area occupied by either species will be referred to in the rest of this report simply as the pinyon-juniper woodland, or zone. The nature of this association and the other species found in the communities have been discussed by Tueller, *et al.* (1979).

Within the geographic area considered, pinyon-juniper woodland does not occupy a very large fraction of the land area. It is not found on most of the valley floors and much of the fan areas above the valley floors. It is found primarily on the lower mountain slopes, particularly in the center of this region. It is not, however, found on all mountain slopes, nor is it excluded from all fan and valley floor areas. Inasmuch as the pattern of pinyon-juniper woodland has not been shown to correspond to any soil or geologic mosaic on the same landscape, it has been assumed in this report that the distribution of the pinyon-juniper woodland within this area may be largely determined by climatic features of the area. Billings (1954), in discussing the vegetation of the Great Basin came to the con-

clusion that the pinyon-juniper zone was associated with a thermal belt around the sides of the mountains. The limited data he collected supports this conclusion. The pinyon-juniper zone also is a zone of intermediate precipitation between that of the desert shrub valley floors and the more moist upper mountain slopes. The pinyon-juniper woodland occupies a band around many mountains, a band in which relatively little weather data has been collected. Those station locations which apparently are in the zone have been locally altered by the human activities that led to the establishment of a weather reporting station. Both pinyon and juniper are relatively slow-growing species whose mode of seed dispersal is complex and their period of juvenile status is quite long. Hence, it is difficult to establish which parts of this complex Great Basin environment are suited to pinyon-juniper but not occupied by them because of past fire or other man-caused disasters, and which parts are only marginally suitable for pinyon-juniper forest and are perhaps most wisely kept in brush or grass for alternate uses of the area. The goal of this project was to establish in sufficient detail the primary characteristics of the climate of the pinyon-juniper zone so that any specific location would be described relative to climatic suitability for pinyon-juniper forest management. Three lines of inquiry were set up: 1) a statistical climatology of the Great Basin using past records and a large area analysis; 2) synoptic climatology involving both large area analysis and local effects analysis; 3) a topoclimatological approach using a water-balance model to describe the local climate variability. This report summarizes the efforts and progress made toward meeting the project goal.

Objective 1: To develop and to test predictive models to estimate precipitation patterns in and adjacent to the pinyon-juniper zone throughout the Great Basin.

The pinyon-juniper zone as a part of a complex climate of the Great Basin lies in a transition between the dry valley floors and the much more moist mountain peaks. Although hundreds of precipitation measuring stations are, or have been, located in the Great Basin, relatively few of them are in areas occupied by the pinyon-juniper woodland. At higher elevations many of

the stations available are storage gauge stations which are visited only occasionally. The station network at lower elevations has varied over time with the relative success of mining, ranching, and other occupations in the Great Basin. Selection of stations in a statistical analysis of precipitation requires a compromise among the desirable maximum density of stations, the non-concurrent character of many of the records, and the large amount of estimation involved in allocating storage gauge precipitation to specific times. Several sets of precipitation data were used in statistical analyses to develop predictive equations for precipitation at any point.

The definition of the boundaries of the study area was critical since it determined the choices of precipitation data for analysis. In Figures 1 to 4 are presented four different area definitions. Figure 1 shows the distribution of singleleaf pinyon as given by Little (1971). On the southwestern border the distribution limits are close to the boundary of the Great Basin shown on Figure 2. The Northern and Eastern boundaries do not match well. Beeson (1974) described the distribution of pinyon-juniper woodland in the Great Basin using satellite imagery. The boundary of his distribution (shown in Figure 3) lies within the Great Basin, except for the irregular part of the southeast portion of the Basin. Most of the Great Basin pinyon-juniper woodland lies north of the Arizona-Utah border. The plant communities surrounding the pinyon-juniper zone are different in the southern part of the Great Basin. In the descriptions of floristic sections of the Great Basin, Cronquist, *et al.* (1972) made this a separate section. The remaining floristic sections of the Great Basin are outlined in Figure 4. The area in Figure 4 with smooth boundaries similar to those of Beeson has been chosen as the primary area for which climatic descriptions were made.

The precipitation data used in prediction equations were selected to cover the same general areas. The first set of data consisted of all stations within a circle drawn around an approximate center of the Great Basin and for which normals of annual precipitation were available. The distribution of these stations is shown in Figure 1. Some of these stations had relatively high precipitation compared with others at the same elevation, and were outside the Great Basin. These were removed from the list to form the

set of data shown in Figure 2. To study the importance of the Sierra Nevada and Wasatch Mountain effects, the stations on the east and northeast margins were removed, leaving the set shown in Figure 3. A fourth selection covering the Great Basin north of 37° latitude (approximately the same as the floristic sections chosen) is shown in Figure 4.

The data for these four sets of stations were analyzed using a stepwise multiple regression analysis program (Koh, 1972). The variables used were: normal annual precipitations (precip), natural logarithm precip., precip^2, latitude, longitude, elevation, elevation^2, natural logarithm elevation, and station number. Two of the many regression equations for each set of data are shown in Figures 5 through 8. In each case equations using Ln(precip) had larger r^2 values than those using (precip) as the dependent variable (the equations using (precip)^2 had even lower r^2 values). None of the equations is fully satisfactory as a predictor of mean annual precipitation. Although statistically, each of the variables is significant, the fraction of the variation in recorded precipitation accounted for is small. Even the curves in Figure 7, for which r^2 is relatively high are not good predictors of precipitation at elevations approaching 10,000 feet. In the equations (with one exception) elevation was the most important independent variable; however, latitude was the next variable for the two sets of data and longitude for the others. Clearly choice of data for analysis affected the results. Additional sets of stations and analyses were employed--the number of possibilities is almost limitless. The stations included both valley stations and storage gauge stations in the mountains. A shorter period of record was used to increase the number of available stations. Storage gauge data were used where the precipitation had previously been allocated to months by the National Weather Service.

As the number of stations increased, the apparent precision of the prediction equations increased only slightly and the logical uncertainity as a result of second and third order approximations and non-overlapping data increased. One of the difficulties in a statistical analysis of this sort is that the logical requirements of the model include independence of

the parameters used to predict precipitation in the Great Basin. The precipitation measuring points are neither spaced evenly on a grid nor distributed randomly. Furthermore, all elevations are not equally represented at all latitudes and longitudes. The roughly oval shape of the area eliminated significant correlation between latitude and longitude; however, the correlations between latitude and elevation, and between longitude and elevation often were significant in various station networks. The 91-station network for which regression equations are presented in Table 1 represents one of many possible compromises among station density, a more or less uniform distribution over the area, and a more or less concurrent set of data. Only a limited number of storage gauge data were included since allocation of storage gauge data to months assumes that the distribution of precipitation in time at the storage gauge location parallels that at recording gauge or standard gauge stations at lower elevations. This probably is a reasonable assumption, but it is an assumption which degrades the quality of data for this kind of regression analysis. In Table 1 the coefficients for the parameters elevation^2, latitude, and longitude for monthly and annual precipitation prediction are presented in that order. Only the coefficients (limited to 3) that were statistically significant are included. The equation for annual precipitation accounts for about fifty percent (50%) of the variation in annual precipitation over the area. The mean precipitation of these stations is approximately ten inches,which is the lower limit usually assigned to precipitation in the pinyon-juniper woodland. This suggests that this station network is biased toward the lower elevation stations, even though an attempt was made to select as many high elevation stations as were consistent with a good areal distribution. The equations for the summer months are better predictors of precipitation than the equations for the winter. This too, is misleading, since the data for the summer months are likely to include more zero values and, as noted by the column headed CV, the standard error of estimate as a fraction of the mean is somewhat lower in the summer months, but not strickingly so. The adequacy of these estimates of precipitation depends upon the intended use. The apparent precision of equations is similar to that for high intensity rainfall for the same area as found by NOAA (Miller, *et al.*, 1973). The equations may represent an improvement over isohyetal maps, particularly for the individual months. Periods between one

month and a year in duration can be estimated by combining the coefficients for each of the monthly equations. Thus, seasonal precipitation data for any season of interest may be synthesized and, in this respect, the equations are an improvement over monthly or annual isohyetal maps.

The variation in r^2 values, and *CV* noted in the monthly analysis, suggested that some seasonal influence not associated with latitude was involved in determining the elevational distribution of precipitation in the Great Basin. There is a rough parallel between the value of r^2 and the percentage of precipitation as ascribed to Pacific-type storms for the various months of the year (Houghton, 1969). This suggested that any improvement the prediction equations would most probably involve use of a synoptic pattern prevailing at the time of precipitation.

Two approaches were used in synoptic analysis of precipitation patterns. One involved mean monthly synoptic patterns and precipitation. The detailed results of this analysis are presented in Appendix A. The other approach involved a detailed daily analysis of synoptic patterns and daily precipitation from selected stations. This information is presented in Appendix B.

The monthly synoptic analysis was a modified statistical analysis in which the independent variables were chosen to represent the statistical interaction between the moisture laden atmosphere and the terrain. The model assumed that the most appropriate starting point for an estimate of mountain precipitation is precipitation measured in a nearby valley. In the model, the generally accepted position that precipitation increases with elevation was used as a starting point. The precipitation at high elevation (*Po*) is calculated by multiplying the precipitation at a nearby valley (*Pq*) by a factor which varies with the geographic position and local terrain. Many possible and rational factors were considered. Statistical analysis reduced the number to less than ten. The best fit equations for estimating precipitation for the various months are presented in Appendix A. Introduction of local terrain factors into the statistical analysis produced equations with a relatively homogenous r^2 throughout the year compared with the variation in the equations of the climatological approach. The goodness of fit

of the equations and, in some cases, the important statistical parameters, unfortunately, are dependent upon the set of data included. Only a limited set of high elevation stations was available and the stations were not uniformly distributed throughout the Great Basin. As predictors of rainfall at a specific location in mountainous terrain, the equations can be considered only approximations.

The monthly synoptic analysis used the longest possible period of record and monthly mean values only. In each case, of course, the monthly values were derived from daily information. The daily synoptic analysis used the individual daily information directly. In this analysis, the occurrence of precipitation was related daily to the synoptic analysis of published maps for the day. On most days it does not rain anywhere in the Great Basin; precipitation is not a part of a prevailing synoptic pattern. Many of the days with precipitation turned out to have mixed synoptic types or were marginally classified as one of the major precipitation source types.

The analysis of the precipitation patterns summarized the daily data in weekly, two-week, and four-week periods. Using the longer periods smoothed out much of the very random nature of the data. Long term precipitation for a month or more is strongly biased by a few large precipitation events and a lot of very small ones. Even in periods with similar long term means, the source of that mean may be quite different precipitation events. This difficulty arises particularly when comparing one station with another. Very rarely does a precipitation event which contributes a substantial amount of water to one location extend over more than a relatively small part of the Great Basin with the same intensity.

The details of the daily synoptic analysis presented in Appendix B illustrate the rare and random character of precipitation events in the Great Basin. They also illustrate the difficulty of analysis of the data for precipitation patterns in relation to the wind. Many of the important storms are associated with windy conditions that make upper level balloon tracking difficult, if not impossible, so a significant portion of the pre-

cipitation events analyzed occurred on days when wind speed and direction were not available. This is a complex statement of the routine observation that precipitation comes in periods of stormy weather. It also illustrates the difficulty of obtaining reliable precipitation data in mountains, particularly during the winter when the precipitation is likely to be snow. The accuracy of snow measurements is much less in windy conditions so that an estimate of mountain precipitation within fifty percent (50%) of the true value is the best that can be expected.

One of the conclusions from the daily synoptic analysis must be that generalizations as to the source of precipitation are not readily extrapolated from one part of the Great Basin to another. This method was not helpful in predicting precipitation. Either a much more thorough and detailed synoptic analysis using several levels of the atmosphere to attempt to locate the source of moist air moving over the Great Basin is required or some, perhaps satellite, cloud movement pattern will be necessary to make this approach suitable for precipitation prediction.

In summary, objective 1 has been partially achieved. Two sets of equations are available for predicting precipitation for monthly or annual mean values for the Great Basin. The error in these equations is probably the same order of magnitude as the error in measuring precipitation in mountainous terrain. Techniques are available (Houghton, 1974; 1969) for estimating distributions of precipitation whose mean values have been established. The analyses used do not take into consideration the effects of the local terrain and wind in producing slope and aspect variations of precipitation within a kilometer square area. No method, short of a very detailed gauge network, is likely to estimate precipitation in these areas accurately, given the state of atmosphere-terrain interaction knowledge.

Objective 2: To develop a predictive model for temperature patterns in the pinyon-juniper zone.

Temperature distribution in the Great Basin is both simpler and more complex than precipitation. Temperature is continuous in that it exists in

all places at all times in contrast to precipitation, which is episodic. Climatological temperature records, however, are not continuous in either time or space. Ordinarily, only the daily maximum temperature and daily minimum temperature are recorded for more than a few airport locations. No accumulator for temperature equivalent to a storage rain gauge has been put into common operation. Not all temperature values are of equal significance to plant climate. Values near freezing are generally of more significance than those further from freezing.

In the lower layers of the free atmosphere temperature decreases with elevation at approximately 1°C per 100 meters in unsaturated air. In the Great Basin area, the air is usually unsaturated, except at the highest elevations. This convenient approximately constant rate does not necessarily apply to temperature profiles at any particular instant in time nor for temperatures at various elevations near the ground on a line up the side of a mountain. Many sets of observations have been made along mountain slopes. Each of these sets, while descriptive of a particular location, is not necessarily suitable for extrapolations to another climatic zone. Some general principles and probable occurrences can be outlined for the Great Basin, particularly for the pinyon-juniper zone. There are a few climatic substations located in the pinyon-juniper zone which can be compared with valley stations to get some idea of the relative temperature conditions in these two physcial positions. Billings (1954) made a series of observations in the Virginia Range near Reno which clearly demonstrated a difference in the thermal regime of slopes in the Great Basin and the valley floors. What follows is a synthesis of ideas developed from Billings (1954), Billings *et al.* (1954), Geiger (1969), Cox (1923), Hayes (1941), Super and Grainger (1969), and Schroeder and Buck (1970).

Maximum and minimum temperatures must be treated separately in comparing slope climates to level topography. Maximum temperatures are derived from the heating of the air layer adjacent to the ground with subsequent conduction and convection to the air above. As the air is heated, it becomes less dense and rises through the overlying cooler air. On a slope, the vertical mixing apparently is as efficient, if not more efficient, as

over a horizontal surface. The extent of heating of the air depends upon slope and aspect as well as time of day and surface conditions. One of the main controlling surface conditions is the availability of water to release the heat produced by absorption of solar radiation in the form of evaporation and transpiration. From this factor alone higher elevations which are supplied with more water have slightly cooler air temperatures than lower elevations. South slope surfaces are much warmer than north slopes, particularly in mid-day, in much of the year. In actual measurements, the aspect differences are less than might be expected partly because the efficiency of mixing of the air near the surface with air higher above increases with the energy input.

In accord with observations, and with expectations based upon atmospheric properties, maximum temperatures probably decrease at approximately the dry adiabatic lapse rate of 1°C per hundred meters. This generalization can be made only for mean weekly or monthly maximum temperature, not for individual days or even weeks. In the dry environment of the Great Basin, the horizontal air flow produced by light winds plus the large net radiation input to heat the air in the absence of evaporation can produce very high temperatures at valley floors without much regard to the elevation of those valley floors. Extreme maximum temperature at Elko is not much different from that at Las Vegas in spite of the large elevation difference. The above generalization, however, probably can be applied with some confidence to extrapolation of valley mean weekly air maximum temperatures to mountain slope mean maximum temperatures within a few tens of kilometers distance and a few hundred meters elevation.

The horizontal and vertical distribution of minimum temperatures is more complex at night when radiation cooling lowers the temperature of the air in contact with and near the ground. The air does not mix with the air above but flows by gravity to a level with the same density. As a consequence of this fairly sluggish flow of air cooled by the surface, valley bottoms accumulate pools of cool air from the surrounding mountain sides. Numerous physical and meteorological processes interact to produce the temperature stratification near the ground at the time of the minimum

temperature. For a particular nighttime radiation cooling situation, the depth of cold air accumulated in the valley depends on the area and slope of the mountain sides that contribute cold air to the valley. The larger the source area, the deeper and colder will be the pool of air in the valley. The flow of air down the mountainside during the night is abruptly terminated when the first solar energy strikes the mountainside and begins to warm the air near the surface; equilibrium is never really established between the source of cold air and the pool in the valley. The rate of air flow down the mountainside depends upon the slope angle and the surface roughness as well as the length of the slope. The analysis of both slope and valley temperatures in the pinyon-juniper zone is, therefore, complex. The flow of air down the side of the mountain will be affected by the presence of, or absence of, the forest and by the extent of canopy closure in a pinyon-juniper woodland. Temperature profiles measured in any particular valley for a short period will not be generalizable to an area as diverse as the Great Basin. Temperature records from stations for long duration in the pinyon-juniper zone provide a basis of comparison with valley stations on an approximate basis. One special compilation of minimum temperatures is the date of last occurrence and first occurrence of freezing temperatures; these are commonly used to define growing season. Growing season maps for Nevada and Utah (Sakamoto *et al.*, 1973; Ashcroft and Richardson, 1969) have been published. The Utah map is particularly informative with respect to the position on the side of the mountains at which the freeze-free period is longest. This corresponds to what is commonly referred to as the top of the inversion layer. In general, this long freeze-free period is approximately 300 meters above the valley floor. This elevation varies as would be expected with the size of the valley, the local relief, and slope.

As a first approximation, the following model of vertical distribution on mountain slopes of minimum temperature is proposed. For the first 200 meters above the valley floor, the mean weekly or monthly minimum temperature increases 2°C per hundred meters. The next 200 meters may be taken as isothermal for mean minimum temperatures. Then the minimum temperature decreases again at the wet adiabatic lapse rate of 0.6°C per hundred meters.

The elevation of the valley floor for use in this model is not necessarily the lowest point in the valley, but some effective base which may be the elevation at which the slope is less than about two percent (2%). (This is area in which vertical movement of air and density differences becomes very small.) This model is a compromise between the extreme inversion conditions which often prevail in the Great Basin (Houghton *et al.*, 1975) and non-inversion conditions in which the minimum temperature decreases at all elevations above the valley floor. This condition is produced by strong advective air flow from the frontal movement thru the area. It also averages the effect of clear, calm, radiatively-cooled nights with the less frequent but still significant cloudy to overcast nights in which the minimum temperature of the valley is higher than that at any point above the valley floor.

Combination of the models proposed for maximum and minimum temperatures produces a model for the mean daily diurnal range of temperature. This model has a maximum diurnal range at the valley floor with a sharp decrease in range up through the first 200 meters, a gradually decreasing range for the next 200 meters, and a more rapidly decreasing range above that to a zero diurnal temperature range projected well above the mountain peaks in the Great Basin. This model assumes that temperature data are available for the valley floor elevation. For valleys which do not have temperature data recorded near the valley floor, probably temperature data from a similar valley with approximately the same latitude and elevation may be used. This model has not been tested with real data in more than a suggestive way. Several years of data would need to be considered from a number of stations (many of which are non-existent) over a wide range of elevation to establish it. Undoubtedly, local variations from this model will be found.

Objective 3: To develop a predictive model for dew point temperature in the pinyon-juniper zone.

The humidity of the air at a location is a combination of the prevailing humidity of the air mass which has moved into that area and local in-

fluences on air humidity. Over most of the earth, the land vegetation or water surface serves as a source of moisture for the air above it so that humidity measured as dew point or vapor pressure decreases with elevation above the surface. (The gradient near the surface may be reversed at night when the surface temperature falls below the dew point temperature.) The decrease in vapor pressure with elevation as a result of upward transport by turbulence of water vapor from the surface is not a simple phenomenon since the difference between the surface vapor pressure and the upper air vapor pressure is limited by saturation vapor pressure of water at the upper air temperature.

In the Great Basin, the local source of water vapor at the surface is absent, or at most, intermittent at lower elevations. Dew point temperatures and vapor pressures are lower in the intermountain west than anywhere else in the continental U. S., with the exception of the North Central Region in winter when the very low temperatures limit the vapor pressure even at the surface. Maps of dew point and vapor pressure have been prepared for the U. S. (Dodd, 1965a; 1965b) and the world (Tunnel, 1958). Although the two sets of maps were prepared in different ways, the results are similar. There are very low dew points over the Great Basin for most of the year with gradients of vapor pressure from the south during most of the year and from the northwest during some parts of the year. Differences in dew point or vapor pressure within the Great Basin, however, are relatively small. Precision of the analysis is extremely poor since there are very few locations which report dew point temperatures. The simplicity of the dew point pattern as measured at airport stations suggests that extrapolation of dew point data from one point to another within the Great Basin is feasible and not subject to major errors.

The vapor pressure of water vapor in the atmosphere in the absence of any additions or removals of water vapor to the air would be expected to fall as the elevation increases in the same way as barometric pressure. In balloon ascent measurements, this simple pattern is not found because of the complication of water vapor additions at the surface. A decrease in vapor pressure is found which is greater than would be expected from the

decrease in barometric pressure. Measurements of vapor pressure made along a mountain slope would not necessarily parallel those in the free atmosphere above the valley because of the effects of the surface. The mixing of air near the mountain slope is less complete than over the valley, so that local effects might be altered somewhat. Since precipitation increases with elevation in the Great Basin, the probability of a local water source for water vapor in the atmosphere increases as elevation increases. The local effects of the mountain slope may nearly offset the usual moisture gradients so that for extrapolation purposes, mean weekly or monthly vapor pressure at a mountain location can be derived from vapor pressure at the valley location using just the barometric pressure correction. This approximation is limited to periods of a week or longer since on a particular day or hour the dew point at different locations in the Great Basin is determined in part by passage of frontal systems. At the division of air masses from various sources fairly sharp discontinuities in vapor pressure may exist. Also in the early morning hours very low surface temperatures may cause local downward gradients of water vapor as dew or frost is formed. Since most of this condensate is evaporated within a few hours the effect on the mean daily vapor pressure over the valleys is relatively small, particularly since dew is common only under relatively calm radiative clear sky conditions. Vapor pressure, at any point in the Great Basin, can be estimated from the available valley stations. Ideally, two or three stations should be used to give a horizontal gradient of vapor pressure for the period of interest and then this horizontal gradient extrapolated to the elevation of interest using barometric pressure corrections. Alternate measures of humidity, such as dew point or relative humidity,can then be derived using local temperatures or even extrapolated temperatures.

Combining the previous temperature model with this dew point model produces a description of the pinyon-juniper zone as one in which the vapor pressure in the air rarely reaches saturation. That is, the relative humidity is almost always below 100%. The data of Billings *et al.* (1954) for a transect in the Virginia Range clearly showed a much lower maximum relative humidity in the pinyon-juniper zone than the valley floor. The mean relative humidity did not change as much with elevation since the minimum

relative humidity of the valley floor was lower than on the slopes as a result of the gradient in maximum temperature. At high elevations the reduction in maximum and minimum temperatures may produce areas in which the relative humidity is higher both at night and during the day than at lower elevations. In terms of plant physiology, the pinyon-juniper zone is a band in which the water vapor gradient is almost always from the plant to the atmosphere. Zones both above and below it may have periods in which condensation and a zero gradient from plant to atmosphere are present. In this respect, the pinyon-juniper zone is not as arid (higher precipitation) as the valley floors, but is more uniformly and continuously dry (vapor pressure gradients from plant to atmosphere) than the valley floors or the higher elevations.

Objective 4: To develop and test the model of effective moisture, based on precipitation, temperature, and dew point for the pinyon-juniper zone of the Great Basin.

When the study plan for this project was written, no specific effective moisture model was considered as the most probable tool for meeting this objective. A wide variety of potential evaportranspiration calculations have been proposed for use in water balance models of one form or another. Jensen (1973), and Doorenbos and Pruitt (1975) have considered many of these models and selected a smaller group for use in irrigated arid areas. All of the methods of calculating potential evapotranspiration assume that the vegetated surface is nearly horizontal and extensive in all directions. For the pinyon-juniper woodland, a model which was readily adaptable to different slopes and aspects was a significant requirement.

In Appendix C the development of a water balance model for the pinyon-juniper zone is presented in detail. This model is based on the variation in solar radiation input on a slope with aspect and season of the year. Solar radiation input is divided into two components--direct and diffuse--to accommodate the continuously shaded north slopes in winter. The radiation input term is modified by terms involving temperature, humidity, and wind. For any location temperature can be extrapolated from available

valley data using the model presented under Objective 2. The humidity may be derived from the dew point extrapolated as outlined under Objective 3 and the extrapolated temperature. No detailed model for wind was investigated in this project; since wind is required in this model only in general levels, data for almost any station can be used to set the approximate wind speed at any location. In mountainous terrain, the wind speed is highly dependent on the position of the point in respect to both the prevailing and the local wind field. The mean wind speed on mountain slopes increases with elevation and probably is significantly greater than that at airport sites. The difficulty of extrapolating wind was one of the reasons for choosing the simpler Makkink model over the generally accepted Penman model for potential evapotranspiration.

Reference crop evapotranspiration (a term preferred by Doorenbos and Pruitt to potential evapotranspiration) may be considered an atmospheric demand or sink strength for evapotranspiration. The source of the water is the precipitation (or at least that portion of it which enters and remains in the soil profile). A simple water balance model may be constructed for any time period using this input and output data. In the pinyon-juniper woodland and neighboring communities, only in the winter months does the mean precipitation supply equal or exceed the mean reference crop evapotranspiration demand, even on a level surface. On the south facing slopes, the mean supply never exceeds the mean atmospheric demand.

To adapt the idea of reference crop evapotranspiration to conditions and plants other than the continuously growing grass cover assumed as a reference, it is necessary to consider some aspects of the water physiology of the plants for less than a freely available water supply in the soil. In this study, the Thornthwaite-Mather (1957) model of actual evapotranspiration and soil water depletion was used. In their model, the ratio of actual to reference crop evapotranspiration declined as the soil water storage declined. A maximum of soil water storage of 100 millimeters was more or less arbitrarily assumed. Only on a few north facing slopes was this exceeded by the precipitation minus actual evapotranspiration term. It was assumed that pinyon and juniper transpire throughout the year when-

ever the temperature is above freezing in the needles. This is an extrapolation of the work Fritts (1976) has summarized. In almost all cases, respiration, transpiration, and photosynthesis were active at all temperatures (near freezing) in the unfrozen needles studied.

The plant transfer function relating soil water supply and transpiration was considered over a range of conditions. A value of the crop coefficient of 0.33 was chosen. This coefficient assumes that under conditions of full soil moisture recharge, the pinyon-juniper woodland will transpire one-third as much as a short grass ground cover in the same location. No literature was found to support a choice of crop coefficient. Since the trees appear to be transpiring in all months, no seasonal variation was made in the crop coefficient. It may well be that in some circumstances a seasonal variation in crop coefficient would be appropriate. For example, on some sites there is a considerable herbaceous seasonally active understory in the woodland. This understory probably adds to the evapotranspiration in its season of activity more than the rest of the year. A crop coefficient of less then 0.33 may be appropriate for open stands with little or no shrub or herbaceous understory.

The examples in Appendix C illustrate the use of the water balance model. The data for the level and north and south facing 30 degree slopes at the various locations present the wide range of water balance possibilities that prevail in the pinyon-juniper zone. The water balance data presented is based on mean values for each of the data inputs. If individual monthly data were used and plotted for a series of years, an even wider range of water balance figures would be obtained. There are, however, certain generalizations that can be made. On the south facing slopes, in almost every case, there is very little storage of precipitation from month to month. Given the variability of precipitation, this suggests that in at least half of the years the moisture available to the woodland on the south facing slopes is dependent primarily upon the distribution of precipitation. A series of dry years, or a series of dry months, would impose a moisture stress on the woodland on south facing slopes. The same series of dry years would affect the north facing slopes to a lesser extent or after a longer

series of dry months, because there appears to be some moisture storage carry-over from month to month, as a consequence of the lower evaportranspiration on the north slopes. The water balances of the east and west facing slopes are similar to that for a level surface and lie between those for the north and south slopes.

The water balance model, although not defining a unique climate of the pinyon-juniper woodland, does provide a basis for estimating the climatic components of plant water environment. In this model it has been assumed that all of the precipitation is added to soil storage and that only precipitation is added to soil storage. This model fails if there are subsurface sources of water which add to the supply of water available to the plants. The position of the woodland on the lower slopes of the mountains is one where the probability of subsurface flow along bedrock or other impermeable areas at some depth below the ground surface is high. Such subsurface flow may not be available to herbaceous and shallow-rooted shrubs, but may be available for the deeper-rooted large trees. Once the trees have penetrated to this moving moisture at depth, the trees would then be relatively insensitive to fluctuations in precipitation moisture supply. Variations of precipitation in both time and space would then be relatively less important and difficult to relate to apparent tree water relations.

General Discussion:

The specific objectives discussed above were designed as a part of a larger scale approach for describing the climate of the pinyon-juniper woodland. It was assumed that there might be a more or less distinctive climate that corresponds to and perhaps limits the distribution of this woodland. The models prepared permit a reasonably accurate, fairly detailed description of the mean climate for any location in the pinyon-juniper woodland. The models also provide for year-to-year variation of the elements of climate and variation in the water balance produced by the climate. The models do not, however, provide a means by which a pinyon-juniper woodland climate may be uniquely distinguished from the climates

of surrounding vegetation. In choosing among models of the pinyon-juniper climate, a wide range of possible climatic limits were considered. Every possibility was found to not be a definite exclusion parameter at some point or other in the woodland. Several speculations will be considered here. Each of them requires for validation more details of the physiology of the species than is now available.

In the work of Billings *et al.* (1954) and Beeson (1974) it was suggested that minimum winter temperatures are involved in limiting the range of pinyon pine, particularly. The minimum temperatures (absolute minimum) are so variable throughout the range of the species that an absolute minimum does not seem an appropriate limitation. Another temperature parameter that might be confounded with the absolute minimum is the daily range of temperatures in the winter. If the pinyon pine is relatively inactive and dormant (in the sense of controlling transpiration at fairly high needle temperatures) in the winter and if the roots or trunk are frozen as the result of low nighttime temperatures and the needles thaw during bright, warm days (this requires a wide diurnal range of temperature in the winter) then the plants could suffer from the desiccation that is commonly encountered in the shrubs and other plants of the snow fields. Under the same circumstances, if a biologic mechanism curtails respiration and photosynthesis at low temperatures, but does not successfully control transpiration then much of the water transpired during the cold season, particularly on the south facing slopes, may not be associated with production of dry matter and thus the effective growing seasons (the period in which dry matter production is not restricted by either low temperature or low soil water supply) may be very short. This could well be the case at Winnemucca. Fritts (1976) has demonstrated that, in general, the length of the growing season is relatively independent of elevation in the Southwestern U. S. At high elevations, the growing season is limited by low temperatures. At low elevations, the growing season is limited by the water supply.

Water supply may be the limiting item in the pinyon-juniper climate in the summer months as well as the winter months. In the water balance model, at some of the locations, the values for actual evapotranspiration

during the warm periods were found to be below ten millimeters per month for one, two, or even three months during late summer. Since these months are relatively warm, respiration of the plants would be high, but photosynthesis might be very low. The result would be a very short period of net dry matter accumulation.

The speculations on the environmental limitations of the pinyon-juniper woodland clearly cannot be established or rejected without more physiological information on the conditions under which growth and development of these trees take place. Furthermore, it may well be that mean climatic conditions are not responsible for the distribution of the woodland. Catastrophic events, best exemplified by forest and range fires, may be the ultimate limiting conditions. St. Andre *et al.* (1965) described in detail a scene of devastation of a pinyon-juniper woodland in the White Mountains, but could find no apparent cause of the high mortality of the trees. J. H. Robertson (personal communication) described a case in Western Nevada where the trees at low elevation were damaged, while those higher on slopes appeared undamaged. These observations are not inconsistent with the consequences of high evaporative conditions coupled with frozen vascular systems producing extreme desiccation of the upper part of the plants. These also are speculations since no measurements have been made. Certainly, the distribution of forest fires produces an almost random distribution of survivors with a bias toward survivors on what were originally harsher, rocky sites where there was not enough vegetation for the fire to spread rapidly and burn completely. The water balance model suggests that slope and aspect variations in the effective moisture climate may be as great as the temporal variations at a location which are shown by the Palmer Drought Index (Sakamoto *et al.*, 1975). The pinyon-juniper woodland of the Great Basin apparently is a local variant of the widespread pinyon-juniper woodlands of North America; its limits may be set more by extreme events or competition rather than by normals of climate.

Climate of the Pinon-Juniper Zone: In Summary:

Climate of the Pinon-Juniper zone is intermediate between the dry deserts and the moist upper slopes. The daily range of temperature is

smaller than at the valley floors and the mean temperature is higher than at the upper slopes. The Pinon-Juniper zone climate is marked by extreme occurrences of drought and both low and high temperature. Locally the moisture environment is highly variable, especially when it is expressed as the atmospheric demand for moisture or reference crop evapotranspiration. The supply of moisture from precipitation may be estimated with moderate accuracy, but it is difficult to ensure that this is the entire moisture supply for the woodland in many circumstances. The climate of a specified site in the Pinon-Juniper woodland can be adequately described, but a definitive climate for the woodland cannot be described.

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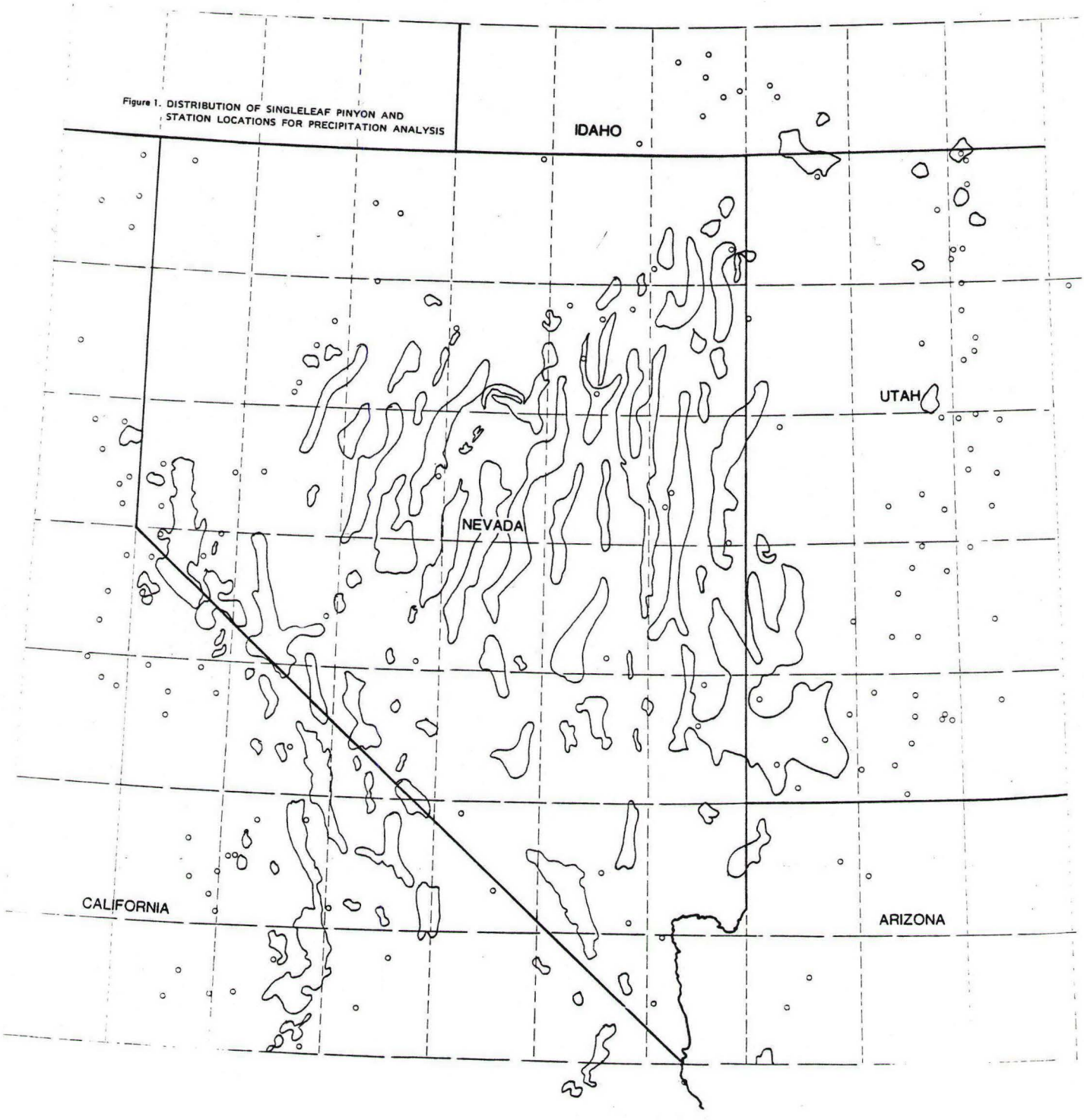


Figure 1. DISTRIBUTION OF SINGLELEAF PINYON AND STATION LOCATIONS FOR PRECIPITATION ANALYSIS

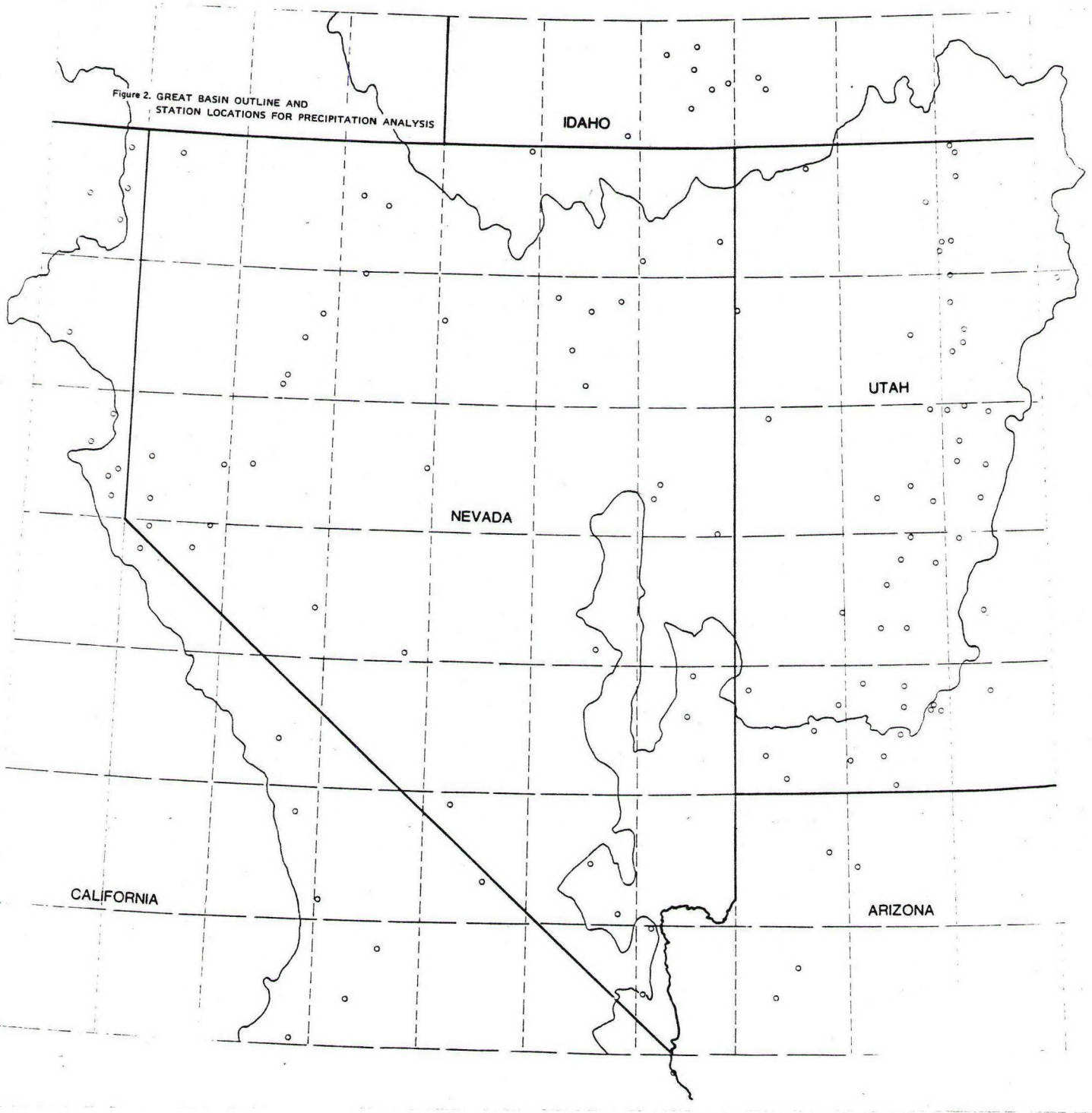


Figure 2. GREAT BASIN OUTLINE AND STATION LOCATIONS FOR PRECIPITATION ANALYSIS

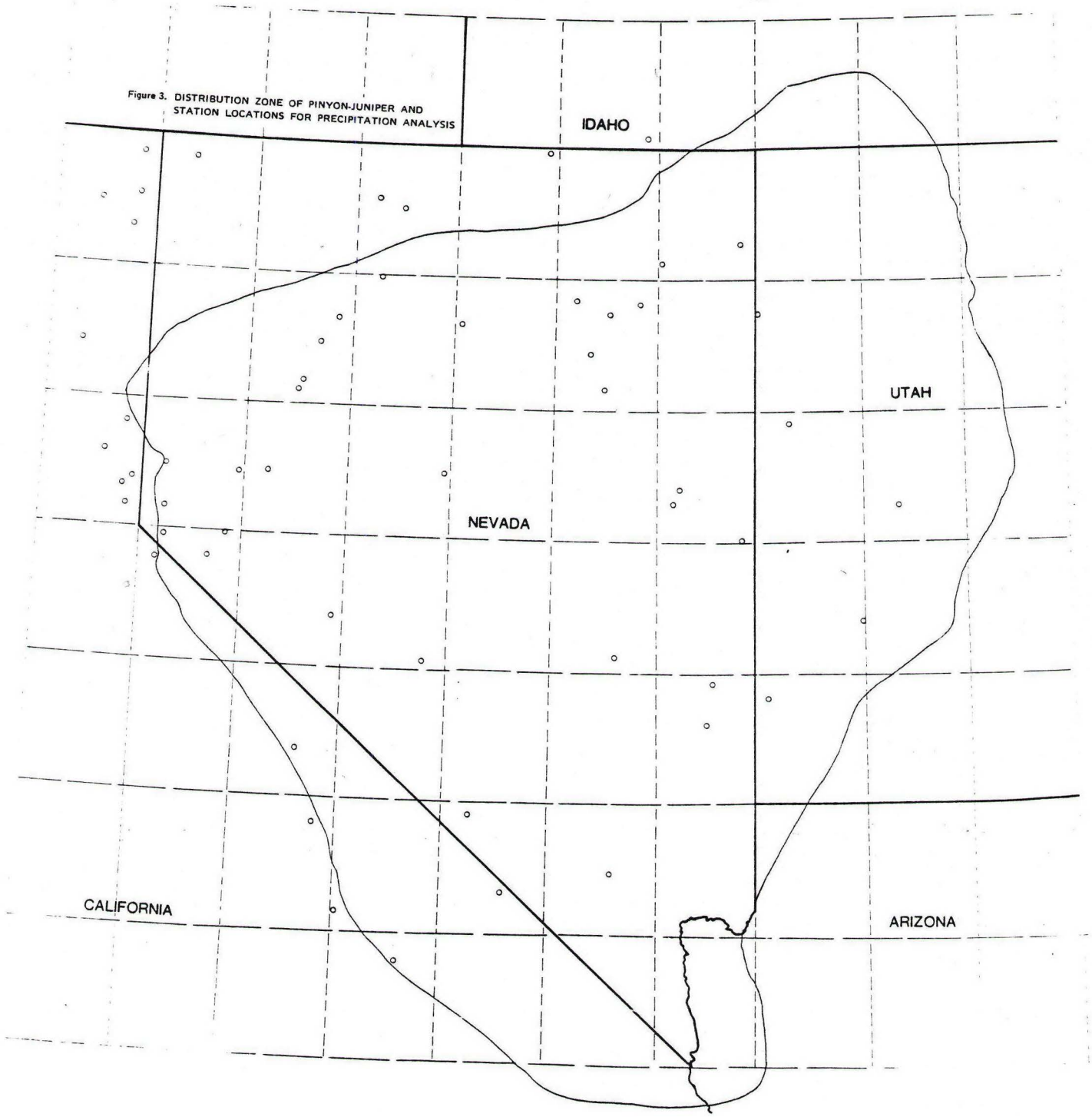


Figure 3. DISTRIBUTION ZONE OF PINYON-JUNIPER AND STATION LOCATIONS FOR PRECIPITATION ANALYSIS

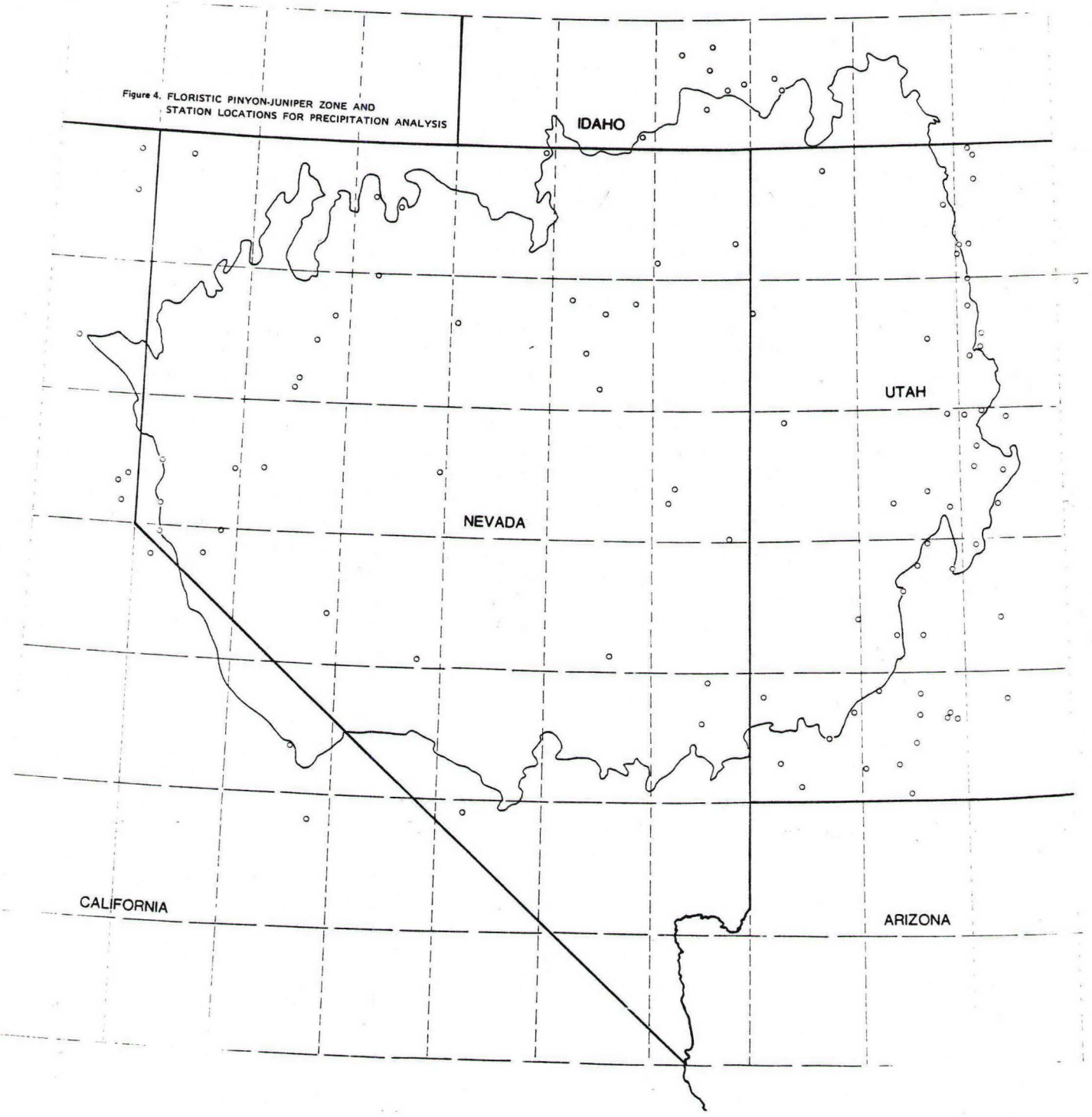


Figure 4. FLORISTIC PINYON-JUNIPER ZONE AND STATION LOCATIONS FOR PRECIPITATION ANALYSIS

Fig. 5 Regression equations for annual precipitation at stations in and near the pinyon-juniper woodland

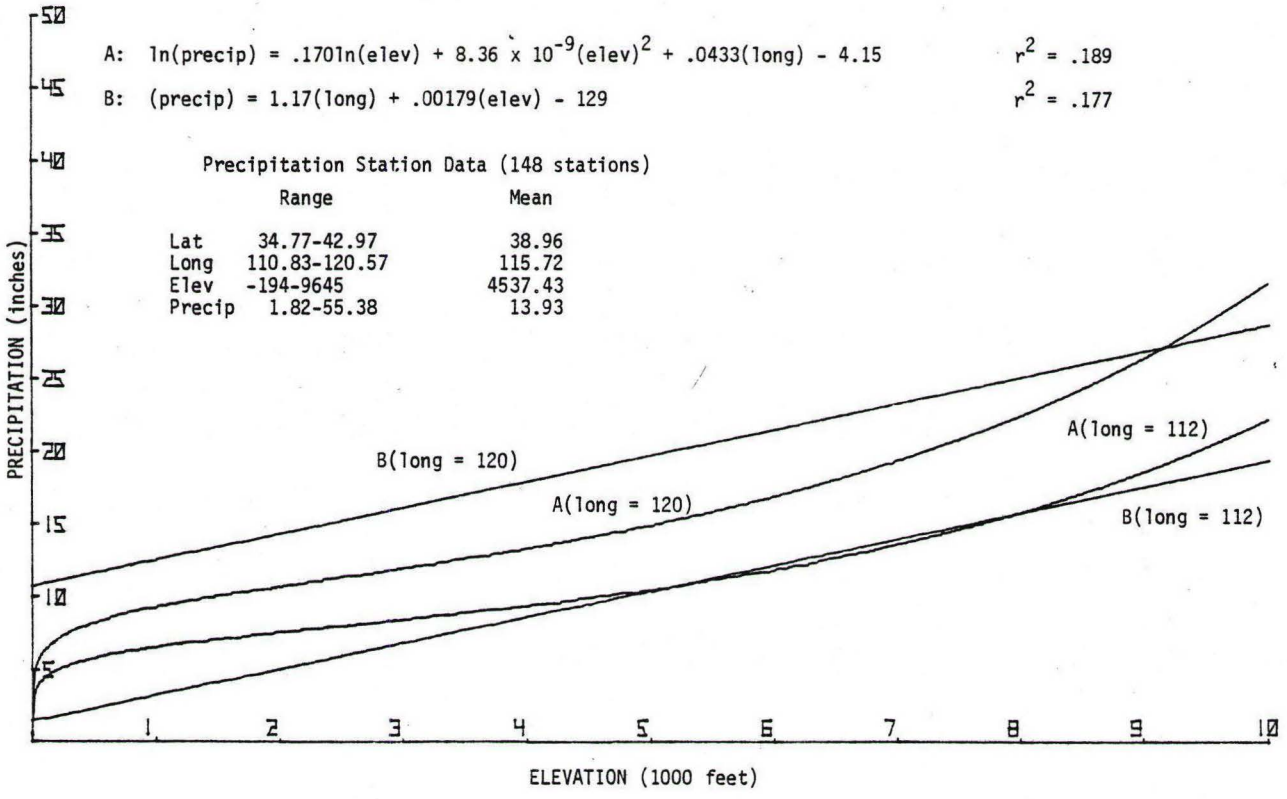

A: ln(precip) = .1701n(elev) + 8.36 x 10^-9(elev)^2 + .0433(long) - 4.15 r^2 = .189
B: (precip) = 1.17(long) + .00179(elev) - 129 r^2 = .177
Precipitation Station Data (148 stations)
Range Mean
Lat 34.77-42.97 38.96
Long 110.83-120.57 115.72
Elev -194-9645 4537.43
Precip 1.82-55.38 13.93
PRECIPITATION (inches)
B(long = 120)
A(long = 120)
A(long = 112)
B(long = 112)
ELEVATION (1000 feet)

Fig.6 Regression equations for annual precipitation at stations in and near the Great Basin

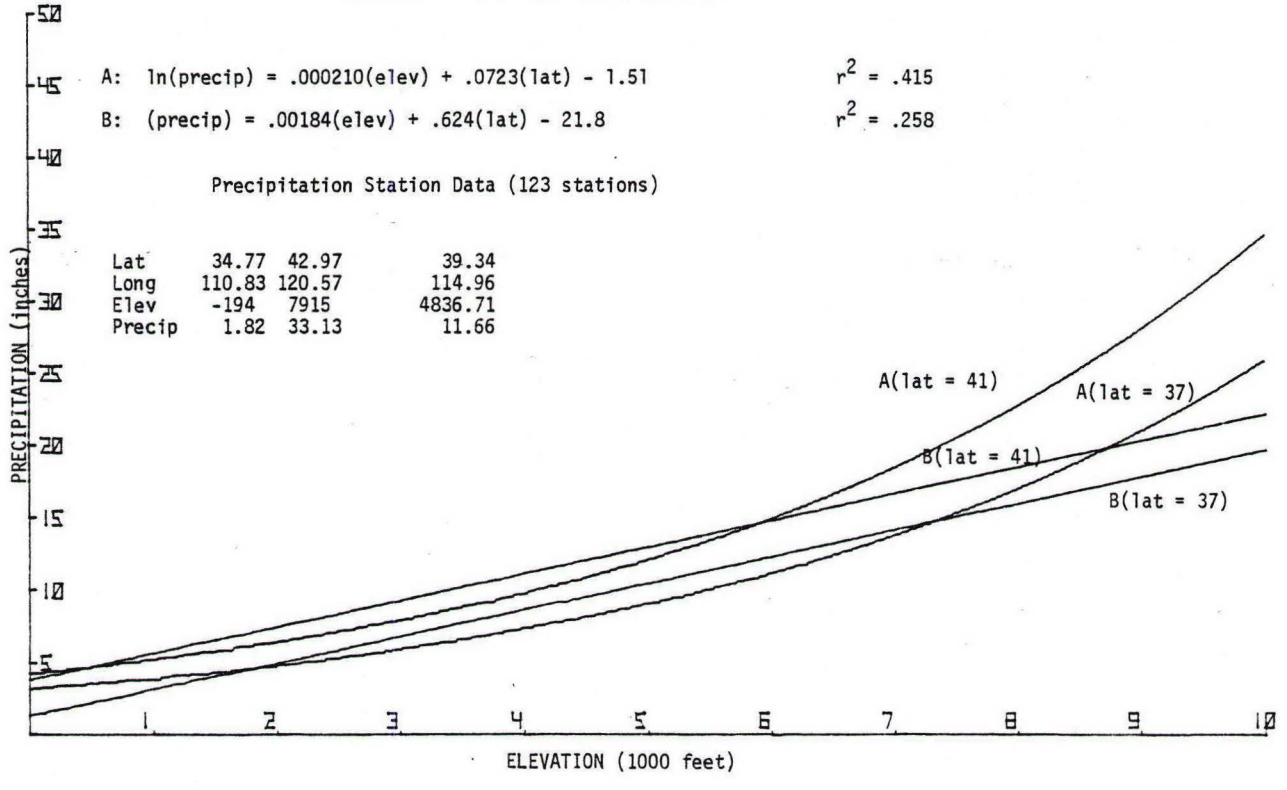

A: ln(precip) = .000210(elev) + .0723(lat) - 1.51 r^2 = .415
B: (precip) = .00184(elev) + .624(lat) - 21.8 r^2 = .258
Precipitation Station Data (123 stations)
Lat 34.77 42.97 39.34
Long 110.83 120.57 114.96
Elev -194 7915 4836.71
Precip 1.82 33.13 11.66
PRECIPITATION (inches)
A(lat = 41)
A(lat = 37)
B(lat = 41)
B(lat = 37)
ELEVATION (1000 feet)

Fig. 7 Regression equations for annual precipitation at stations in the western portion of the Great Basin

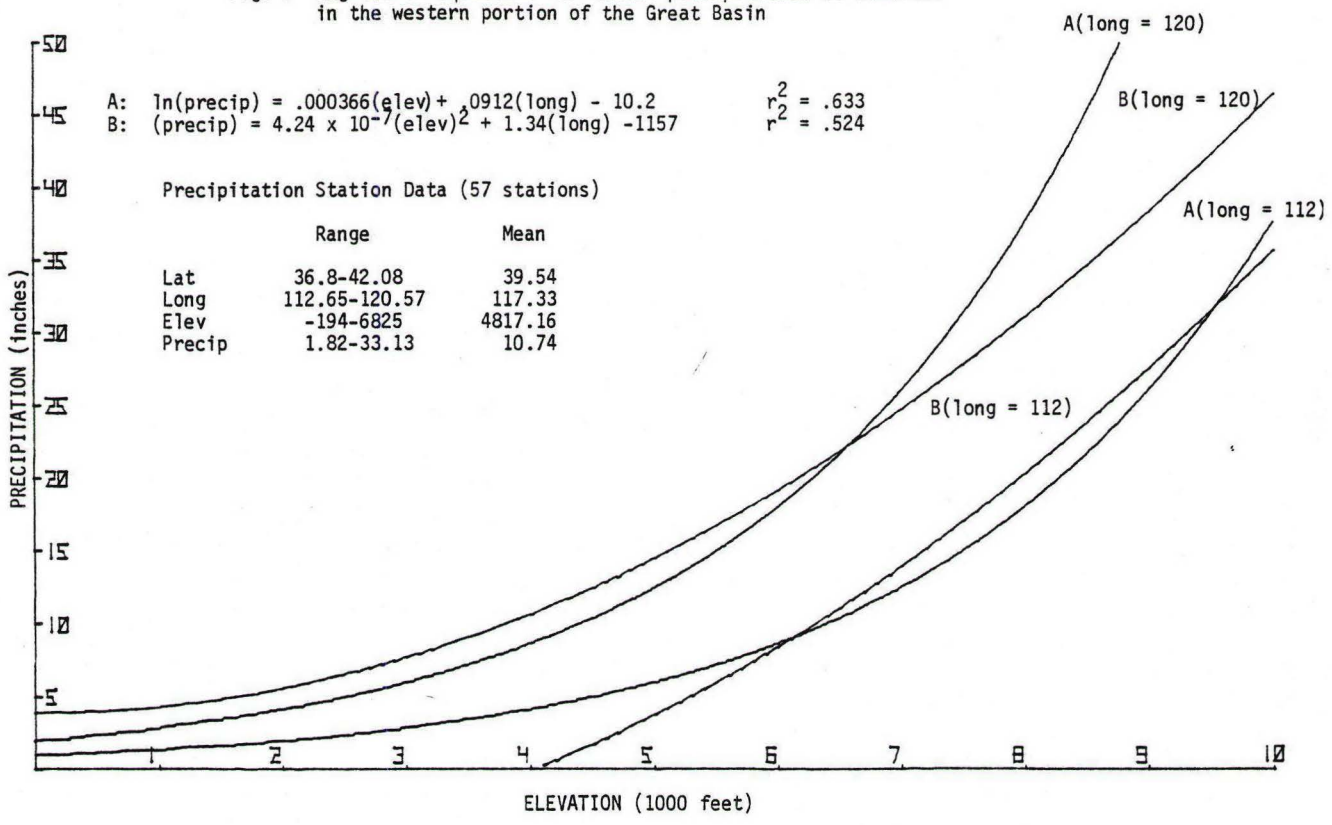
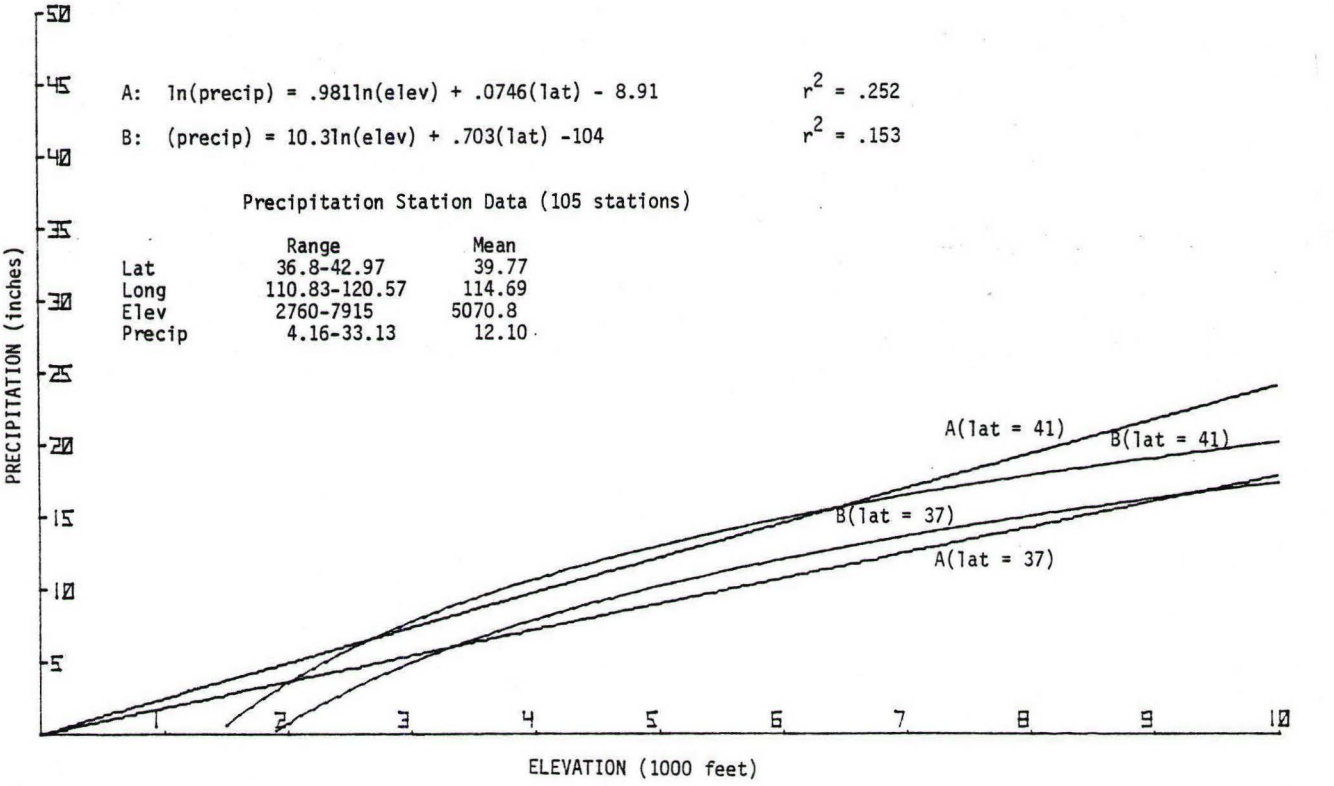

A: ln(precip) = .000366(elev) + .0912(long) - 10.2 r^2 = .633
B: (precip) = 4.24 x 10^{-7}(elev)^2 + 1.34(long) -1157 r^2 = .524
Precipitation Station Data (57 stations)
Range Mean
Lat 36.8-42.08 39.54
Long 112.65-120.57 117.33
Elev -194-6825 4817.16
Precip 1.82-33.13 10.74
A(long = 120)
B(long = 120)
A(long = 112)
B(long = 112)
PRECIPITATION (inches)
ELEVATION (1000 feet)

Fig. 8 Regression equations for annual precipitation at stations in the Great Basin north of 37°N Latitude


A: ln(precip) = .981ln(elev) + .0746(lat) - 8.91 r^2 = .252
B: (precip) = 10.3ln(elev) + .703(lat) -104 r^2 = .153
Precipitation Station Data (105 stations)
Range Mean
Lat 36.8-42.97 39.77
Long 110.83-120.57 114.69
Elev 2760-7915 5070.8
Precip 4.16-33.13 12.10
A(lat = 41)
B(lat = 41)
B(lat = 37)
A(lat = 37)
PRECIPITATION (inches)
ELEVATION (1000 feet)

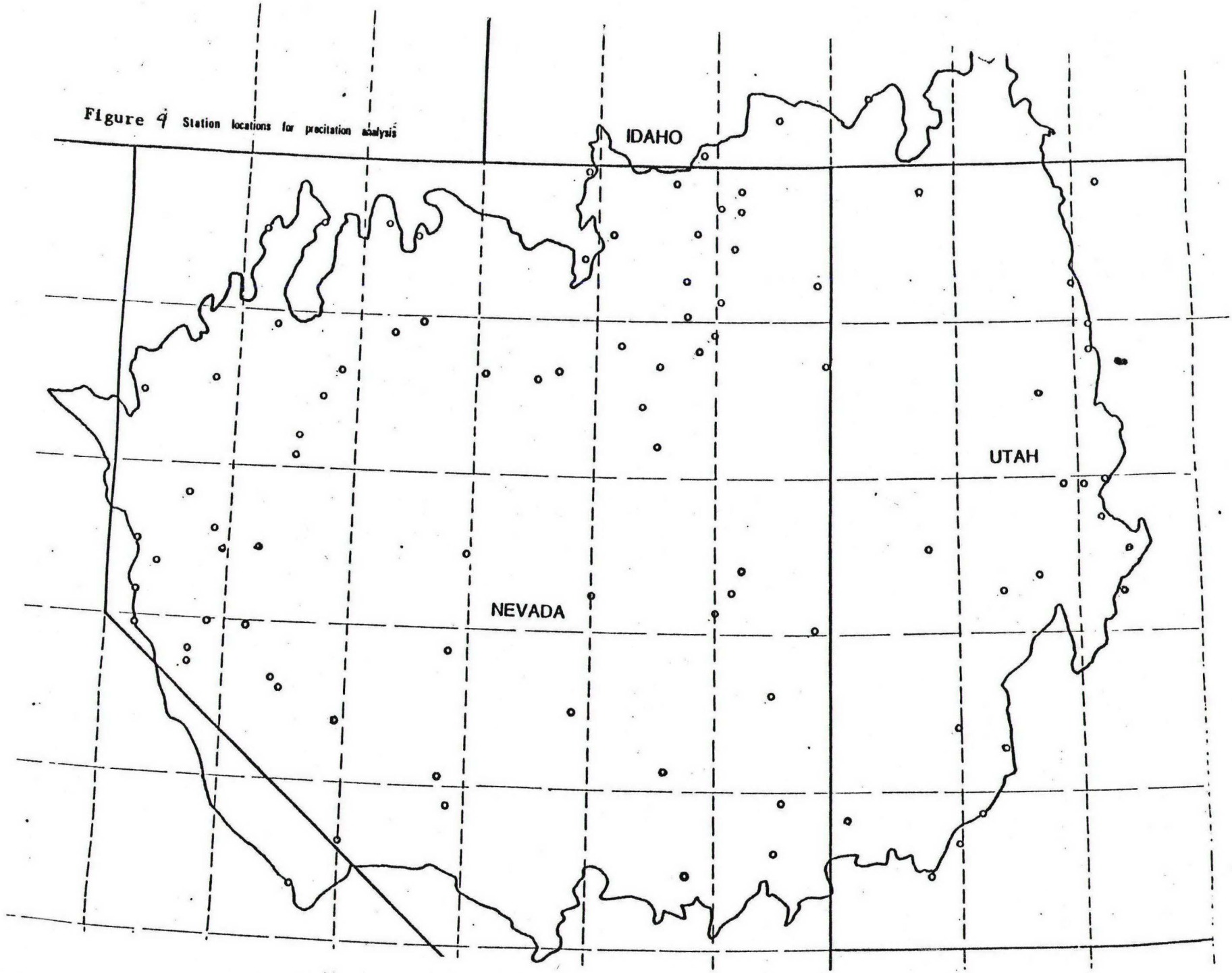


Figure 9 Station locations for precitation analysis

TABLE 1 Multiple Regression Analysis of Pinyon-Juniper Zone Precipitation Data

Period	mean pptn in	r^2	CV %	Equation
year	9.70	.51	29	$Pptn = 57.4 - .71(Lon) + 1.46 \times 10^{-7}(El)^2 + .77(Lat)$
Jan	.98	.17	42	$Pptn = -3.5 + 1.58 \times 10^{-4}(El) + .093(Lat)$
Feb	.86	.21	40	$Pptn = .4 + 1.58 \times 10^{-8}(El)^2$
Mar	.92	.47	39	$Pptn = 9.9 - .082(Lon) + 1.86 \times 10^{-8}(El)^2$
Apr	.93	.53	40	$Pptn = 10.1 - .116(Lon) + .0961(Lat) + 1.47 \times 10^{-8}(El)^2$
May	.99	.63	30	$Pptn = -1.8 + .222(Lat) - .0562(Lon) + 1.47 \times 10^{-8}(El)^2$
Jun	.86	.69	29	$Pptn = -3.1 + .231(Lat) - .051(Lon) + 1.21 \times 10^{-4}(El)$
Jul	.47	.74	29	$Pptn = 10.0 - .0585(Lon) - .0754(Lat) + .912 \times 10^{-8}(El)^2$
Aug	.58	.78	30	$Pptn = 15.7 - .107(Lon) - .0785(Lat) + 8.09 \times 10^{-5}(El)$
Sep	.48	.70	25	$Pptn = 7.6 - .0629(Lon) + 5.55 \times 10^{-9}(El)^2$
Oct	.73	.52	32	$Pptn = 7.5 - .0738(Lon) + 7.97 \times 10^{-9}(El)^2 + .0399(Lat)$
Nov	.88	.34	36	$Pptn = 2.6 - .0467(Lon) + .0854(Lat) + 1.17 \times 10^{-8}(El)^2$
Dec	1.01	.44	41	$Pptn = -2.7 + 1.84 \times 10^{-8}(El)^2 + .0801(Lat)$

Mean pptn = Average of 91 locations (shown in Figure 1)

r^2 = fraction of variation in precipitation accounted for by the variables in the regression equation

CV = coefficient of variation - adjusted standard error of estimate as a percentage of the mean precipitation

The regression equations include the first three statistically significant variables in the order of their importance.

APPENDIX A

A Model for orographic precipitation in the north-central Great Basin

John G. Houghton

Monthly Weather Review 107:1462-1475, 1979

APPENDIX B

Synoptic patterns and precipitation in the pinyon-juniper zone of the Great Basin

Alice R.W. Presley

Master of Science Thesis University of Nevada
Reno 1978

APPENDIX C

A radiation based water balance model for the pinyon-juniper woodland of the Great Basin

Robert R.J. Mohler

Master of Science Thesis University of Nevada
Reno 1979